



## A COMPREHENSIVE MITIGATION ASSESSMENT PROCESS (COMAP) FOR THE EVALUATION OF FORESTRY MITIGATION OPTIONS

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**Abstract**—Carbon emissions from land-use change in the tropics contribute significantly to global greenhouse gas emissions. The evaluation of carbon flows from land-use change and the associated socioeconomic impacts are just beginning for the tropical countries. This paper presents a comprehensive mitigation assessment process (COMAP) for the evaluation of forest sector mitigation options. COMAP is a bottom-up methodological framework which was used in the assessment of carbon sequestration potential by the F7 countries and is recommended in the IPCC 1995 Working Group II chapter. COMAP helps to account for carbon and monetary flows, and to develop scenarios and cost-effectiveness indicators of alternative mitigation options. The COMAP calculation method is coded in a spreadsheet format.

**Keywords**—Carbon; mitigation options; cost-effectiveness; scenarios; COMAP

### 1. INTRODUCTION

The Intergovernmental Panel on Climate Change estimated that annual emissions of carbon from fossil fuel combustion amounted to  $6.0 \pm 0.5$  billion tonnes/year and from land use change to  $1.6 \pm 1.0$  billion tonnes/year.<sup>1</sup> The net emissions from fossil fuel use are largely concentrated in industrialized countries, whereas the net emissions from land use change are largely concentrated in the developing countries. Forests from the high- and mid-latitudes are estimated to be sequestering net carbon on the order of  $0.70 \pm 0.2$  billion tonnes/year.<sup>2</sup> The low-latitude countries, which are mostly developing nations, are the primary sources of net carbon emissions from land use change, estimated at  $1.6 \pm 0.4$  billion tonnes/year.

What is the level of emissions from the major tropical countries? What mitigation options might be pursued to reduce emissions and/or increase sequestration? An earlier set of studies by a network of researchers on forestry and climate change (the F-7 network), whose work is reported in this volume, addressed these questions for Brazil, China, India, Indonesia, Malaysia, Mexico, Nigeria, Tanzania and Thailand.<sup>3</sup> These countries represented about two-thirds of the deforestation in the late 1980s.

The F-7 studies differed from previous ones in several ways: (i) they used a common framework and model (COPATH) for accounting of carbon flows; (ii) both temperate and tropical forests were included for China and Mexico; and (iii) regeneration of biomass on harvested and converted forest lands was included. The F-7 carbon flow estimates were significantly higher for Mexico and lower for Brazil and India than earlier ones,<sup>4,5</sup> due in part to the use of a common method, new in-country data and the inclusion of regeneration.

However, in order to prepare national plans on policies and measures to stabilize future GHG emissions, national policy-makers need information on the costs and benefits of options in addition to their carbon implications. Policy-makers must weigh the costs, benefits, and impacts of climate change mitigation and adaptation options, in the face of competition for limited government funding. The policy goal for land use climate change response options is to identify which mix of options is likely to best achieve the stated forestry goal at the least cost, while attempting to maximize economic and social benefits, and minimize environmental and social impacts.

Improved national-level cost estimates of forest response options can be generated by estimating and comparing the costs and benefits of different forest management practices appropriate for specific country conditions

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and performing land availability analyses for forest and degraded lands potentially available for reforestation or other options, reflecting opportunity cost of land and local and national development priorities. These cost and land use estimates can be combined to develop cost curves,<sup>6,7</sup> which would assist policy-makers in formulating policies and programs to implement forest responses.

The set of papers in this volume evaluate and estimate costs and benefits of land use change options for several developing countries. In this paper, we focus the discussion on the approach used in these studies for the evaluation of the costs and benefits of each option, and discuss the methodological issues that arose in the implementation of the approach. The methodological issues relate to: (i) categorization of forestry mitigation options; (ii) assessment of land availability; (iii) accounting for the carbon flows and costs and benefits; and (iv) the relationship between sustainability and the development of scenarios.

### 1.1. Background

The analyses of the costs, benefits and economics of forest response options have varied in the extent and treatment of components which should be included in the analysis of mitigation options. Table 1 summarizes the components arranged from those commonly included to those least addressed in the analyses.

Studies of the costs of mitigation options have evolved in complexity and specificity of data over the last few years. The initial studies<sup>8,9,10</sup> assumed a large programmatic goal and estimated land requirements and vegetation growth rates to meet it. These studies have largely been replaced by more detailed bottom-up studies.<sup>6,7,11,12,13</sup> The bottom-up studies use economic and physical data at the project and mitigation option level and report results at the national or global level. However,

they do not capture the dynamics of the wood-product and land-use market explicitly. Dynamic studies<sup>14</sup> portray forest product markets, and include timber prices either exogenously or endogenously, and allow land to move between forests and other land uses in response to changes in price or land availability constraints. These studies are more appropriate to industrialized countries where formal wood-product and land-use markets exist, and property rights are well defined. Since these markets are far from perfect in the developing countries, the studies reported in this volume rely on a bottom-up approach in this paper.

### 1.2. Overview of the analytical approach

Each study paper in this volume followed the Comprehensive Mitigation Assessment Process (COMAP) shown in Figure 1. The methodological elements of this approach evolved thorough discussions among the study participants over a 1 year period. The approach consists of:

- (a) identification and categorization of the mitigation options appropriate for carbon sequestration for each country;
- (b) assessment of the current and future land area available for these mitigation options;
- (c) assessment of the current and future wood-product demand;
- (d) determination of the land area and wood production scenarios by mitigation option;
- (d) estimation of the carbon sequestration per unit area for major available land classes, by mitigation option;
- (e) estimation of the unit costs and benefits;
- (f) evaluation of cost-effectiveness indicators;
- (g) development of future carbon sequestration and cost scenarios;
- (h) exploration of the policies, institutional arrangements and incentives necessary for the implementation of options; and

Table 1. Components addressed in mitigation assessments

1.	Infrastructure and establishment costs
2.	Land and growing stock costs (opportunity)
3.	Monetary benefits (revenue)
4.	Non-monetizable costs and benefits
5.	Net present value of continuous rotations over a finite (fixed) or infinite period (perpetual)
6.	Capital requirements
7.	Project or regional economic impacts
8.	Macroeconomic impacts at national level (employment)
9.	Other environmental impacts (biodiversity, water quality)

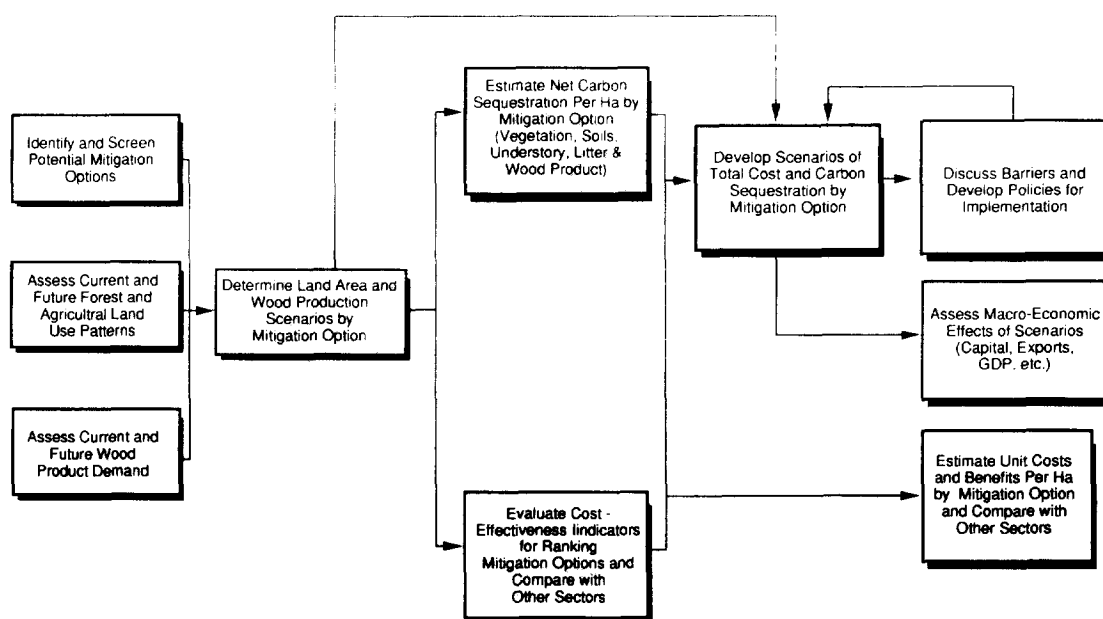


Fig. 1. Comprehensive approach to evaluation of forestry mitigation options.

(i) estimation of the national macro-economic effects of these scenarios (not reported in this paper).

The first step in the approach is to identify and categorize the mitigation options that are suitable for implementation in a country. The next step is to determine the forest and agricultural land area that might be available to meet current and future demand, both domestic and foreign, for wood products, and for land. Demand for wood products includes that for fuel wood, industrial wood products, construction timber, etc. Potentially surplus land in the future may be used solely for carbon sequestration or other environmental purposes. On the other hand, in many countries not enough land may be available, in which case some of the wood demand may have to be met through increased wood imports or through substitute fuel sources (e.g. kerosene or LPG). Alternative combinations of future land use and wood product demand patterns will lead to different scenarios for the future. The most likely trends scenario is chosen as the baseline scenario, against which the others are compared.

The mitigation options are then matched with the types of future wood-products that will be demanded and with the type of land that will be available. This matching requires iterating between satisfying the demand for wood

products and land availability considerations. Based on this information, the potential for carbon sequestration and the costs and benefits per hectare of each mitigation option are determined. The carbon and cost and benefit information is used to establish the cost-effectiveness of each option, which yields its ranking among other options. In addition, the information, in combination with land use scenarios, is used to estimate the total and average cost of carbon sequestration. Finally, the barriers, policies and incentives needed for the implementation of each scenario are explored.

Assessment of the macro-economic effects of each scenario, on employment, balance of payments, gross domestic product, and capital investment, may be carried out using formal economic models or a simple assessment methodology.<sup>15</sup>

## 2. IDENTIFYING AND CATEGORIZING FORESTRY MITIGATION OPTIONS

The main purpose of forestry mitigation options is terrestrial carbon storage, which would reduce atmospheric accumulation and thus delay its impact on global climate. Mitigation options may be classified into three basic types.<sup>16</sup> One option is to expand vegetation stocks and the pool of carbon in wood products. Expansion will capture carbon from the

atmosphere and maintain it on land over decades. The second option is to maintain the existing stands of trees and the proportion of forest products currently in use. Maintenance of existing stands, whether achieved through reduced deforestation, forest protection or through improved cook stoves, lengthens the duration the carbon stays trapped in trees and provides immediate carbon benefit. For example, tropical forest vegetation and soils contain 20–100 times the amount of carbon in croplands and pasture cleared from the forest. Hence maintenance of forests is a much more effective mitigation option, but difficult to implement, since the land is often far more valuable deforested than forested.<sup>17</sup>

A third avenue to reduce carbon emissions is to substitute wood derived from renewable sources, e.g. plantations, for other products, particularly fossil fuels.<sup>18</sup> Fossil fuel substitution with biomass derived from sustainably managed renewable sources, will: (i) delay the release of carbon from fossil fuel until it is needed sometime in the future; (ii) increase standing stock of forests; and (iii) maintain their carbon sinks.

In the papers in this volume, the types of mitigation options that were evaluated were chosen by country analysts, based on the feasibility of options under prevailing conditions. Options assessed include forest protection, improved forest management, the use of improved cook stoves, short- and long-rotation forest plantations, agroforestry and natural regeneration. In some countries, options related to improved harvest systems were considered as well. Some of the papers in this volume examine the expanded use of timber and non-timber wood products. However, the option of substituting wood fuel for other fossil fuels was not evaluated.

### 3. LAND USE AND WOOD-PRODUCT DEMAND

The technical availability of land for the implementation of response options does not appear to be an important constraint to carbon sequestration in the tropics.<sup>9</sup> Dixon *et al.* concluded that land which is technically available in the tropics for expanded management and agroforestry ranged from 620 million to 2 billion hectares.<sup>19</sup> A subsequent survey concluded that 950 million hectares may be available.<sup>2</sup> The studies in this volume confirm that land availability *per se* is not a problem.

Millions of hectares of degraded lands are a common feature of the landscape in virtually every country. In many instances these lands were forested until recently, and they retain adequate soil fertility to support biomass growth. However, the socio-economic availability of land deemed technically available is less studied. In many countries the dynamics of the economy shapes the scarcity of land. Whether technically available lands are ever used for biomass growth depends on economic, political, demographic, social, cultural and other factors. Based on interviews with experts, Trexler *et al.* reported that it was socio-economically feasible to utilize about 69% of the technically available land.<sup>11</sup>

The availability of land for afforestation and reforestation was estimated differently in each study country. China and Thailand based their estimates on a government target for forest cover for the entire country, of 12.8% and 40%, respectively. The figures for India and Mexico were computed on the basis of matching the mitigation options to the types of lands that were technically available.

Large-scale implementation of response options may require legislative, regulatory and institutional changes, such as the 1980 Forest Conservation Act in India, the banning of commercial logging in Thailand in 1989, the removal of tax subsidies for ranchers in Brazil, and the recent constitutional amendment on land-use policy in Mexico.<sup>3</sup> These policies are consistent with carbon mitigation, and their strict enforcement has the potential to alter land use patterns towards more sustainable utilization.

#### 3.1. Scenarios

An important element of the approach used in this set of papers was the development of scenarios of land use and wood products demand. These scenarios depicted the amount of wood that would be demanded and the land that would be required to sequester carbon by mitigation options over time. The amount of carbon that can be potentially stored, and its cost, varies with the types of options that are included in the scenarios. At least four different types of scenarios may be visualized for the future. These are:

(1) *Baseline or Likely Trends Scenario*: this type of scenario would be based on the extrapolation of current trends for land use,

tree planting and forest protection. With the notable exception of India, most developing countries are still deforesting, and this scenario may show little or no net carbon storage for them.

(2) *Technical Potential Scenario*: this scenario helps to estimate the amount of carbon that might be stored if the technically available land area were to be fully utilized for carbon sequestration. This scenario ignores the many factors—socio-economic, institutional, cultural, legal, etc.—that may limit the usability of the technically available land for the purpose of storing carbon alone. Thus the scenario represents an upper limit to the amount of carbon that might be stored through forestry options in a country.

(3) *Programmatic Scenario*: a programmatic scenario would be driven by programs to promote the rapid adoption of mitigation options through the pursuit of appropriate policies. An example of this approach was the America the Beautiful reforestation program,<sup>9</sup> and another was the goal declared by the Noordwijk Conference on Atmospheric Pollution and Climate Change to increase world net forests by 12 million hectares per year in the beginning of the next century.<sup>20</sup> These types of programmatic scenarios were examined in China and Thailand, for example, where the government has set targets for the percentage of future land which is to be occupied by forests.

One disadvantage of a programmatic scenario is that it may yield wood far in excess of its domestic and/or export demand. This may lower the stumpage price of wood and reduce an option's net monetary benefit. Programmatic scenarios may create an inequitable distribution of benefits,<sup>14</sup> since they are driven by a single purpose, i.e. to store carbon, and ignore other impacts.

(4) *End-use Scenario*: this type of scenario is driven by the projections of the demand for wood products and land in a country. The end-use approach has been used extensively to understand the magnitude of future demand for energy.<sup>21,22</sup> However, while it has been used routinely to determine the future demand for forest products,<sup>23</sup> the use of this approach has not been reported in the climate change mitigation context.

End-use scenarios have the advantage that they take into consideration an end-user's needs for forest products and land. In tropical countries, where wood may be scarce and

forests are used as sources of many non-timber products, planting trees for carbon storage alone may not be sustainable or politically justifiable. The trees will most likely be cut and used for their varied products. Thus, forestry mitigation options that provide multiple and adequate benefits, including carbon storage, to a diverse set of beneficiaries are more likely to be implemented and managed sustainably.<sup>24</sup> In order to satisfy our central assumption that tree stock should be maintained in perpetuity, it is important that all participants in an option be adequately compensated. An end-use based approach, which explicitly recognizes the needs of the participants, is likely to yield more plausible and sustainable future scenarios than a programmatic approach

#### 4. EVALUATION OF ANTHROPOGENIC CARBON FLOWS

There exist large uncertainties on the rate and extent to which carbon is removed by natural processes such as erosion and deposited in water bodies. This component of carbon flow is not explicitly considered in this paper.

The aforementioned mitigation options either maintain or expand the stock of carbon in biomass, soil and/or wood products. Two approaches have been used in the past to evaluate the value of stored carbon. The 'plant and store' approach assumes that trees will be planted for the purpose of storing carbon and will not be harvested after they grow to maturity.<sup>25</sup> Hence, it suggests that carbon stock be estimated on the basis of the amount accumulated in forest biomass, soil, litter and understory over a period of time. The time period may be that of a single rotation or of multiple rotations. The 'sustainable rotations' approach assumes that carbon will need to be stored for an indefinite period. It estimates the amount of stored carbon on the basis of an average amount of carbon on-site over an indefinite number of rotations (Appendix A).<sup>7</sup> Harvested stock can be stored in carbon storage pools (e.g. furniture) or substituted for fossil fuels to avoid delayed emissions.

A modified version of the second approach has been used by Swisher,<sup>12</sup> which adjusts average stock for the biomass remaining at maturity. Swisher also includes the carbon in soil, litter and understory and wood products in estimating the total carbon storage.

#### 4.1. Value of stored carbon<sup>26</sup>

Which of these two approaches is appropriate to pursue from a carbon and an economic perspective? The answer to this question will influence the ranking of the mitigation options, and the issues that deserve more attention in the implementation of such options. The 'plant and store' approach will create a larger carbon pool than the 'sustainable rotations' one, but it will not generate a regular income stream. We therefore prefer the 'sustainable rotations' approach, since harvest after rotation provides a periodic income stream,<sup>13</sup> as well as providing timber to meet the growing demand for forest products, which is projected to increase by 50% by 2025.<sup>26</sup> In addition, regular income will act as an incentive to farmers to ensure survival of the planted trees.

Mitigation options store carbon and keep it from being released to the atmosphere for varying lengths of time. The economic value of storing carbon will depend on the damage being caused by atmospheric carbon at the time the carbon was stored and at the time it is released to the atmosphere. If the discounted economic damage being caused by atmospheric carbon is higher when the stored carbon is released, then a mitigation option would cause more economic damage and vice versa.<sup>26</sup>

However, there is great uncertainty regarding the rate at which damage, caused by higher greenhouse gas concentrations, might increase in the future.<sup>27</sup> The uncertainty about future damage is compounded by the possibility of catastrophic damages, and that of moving to a radically different new equilibrium state, which will, by definition, invalidate any prior assumptions on value of economic damage and discount rates. Given our limited knowledge regarding the rate at which the economic damage might increase, our approach assumes that: (i) the damage will increase at the rate of discount; and (ii) everything else being equal, the expected economic damage will respectively influence the rate of discount. An important implication of this assumption is that the discounted economic value of damage caused by a unit of atmospheric carbon does not change over time. Therefore, the implied course of action would be to create a stock of carbon in the biosphere which would last in perpetuity. This assumption about creating a perpetual stock of carbon has important implications for evaluating the carbon flows and the costs and

benefits of options, which are discussed in the following section.

How likely is it that forests may be managed sustainably or that carbon stored in wood products will be renewed continually? Historical data on physical quantities<sup>23</sup> and prices<sup>28</sup> indicate that wood products are usually replenished by similar wood products. Further, forest management practices in many industrialized countries are increasingly moving towards more sustainable systems, though considerable debate exists about their definition at present.<sup>29</sup> Developing countries are beginning to practice more sustainable natural forest management in response to dwindling forest resources.<sup>30</sup> Sustainable management and the continuous replenishment of wood products provides a way to store carbon on land and in products indefinitely.

#### 4.2. Incremental carbon storage

In order to evaluate the incremental carbon benefit of a mitigation option, it is necessary to estimate the carbon that might have been stored without the project. For forest protection, the amount of carbon stored may be estimated on the basis of that which would have been released in the absence of a protection measure, such as a physical barrier or relocation of dwellers.<sup>12</sup> In the case of plantations or management of forests under rotation, the case is more complicated. We need to compare the incremental carbon which would be sequestered in vegetation, soil and the decomposing biomass and in products indefinitely. On land, carbon will be stored. The carbon stored per hectare of a plantation or forest, managed in rotations sustainably, can be estimated using the method shown in Appendix A.

Richards *et al.* report for the US that the accumulation of tree carbon comprises about 80% of the total carbon in their 160 year simulation, soil carbon accounts for 15% of the total and litter contains most of the balance of the total carbon.<sup>31</sup> Estimates of the distribution of carbon between above-ground vegetation and soils vary significantly by ecosystem.<sup>32</sup> However, counting vegetation and soil carbon would include the bulk of the total carbon captured by a mitigation option.

Ideally, carbon stored in wood products should be included when estimating the carbon stored by mitigation options, since wood-product carbon can amount to 30–40% of that stored in forests.<sup>33</sup> Further, Harmon *et al.*

found that 57% of old-growth forest tree boles harvested went into short-term and 43% into longer-term (over 5 years) forest product carbon pools.<sup>34</sup> This ratio of long- to short-term storage may be high given the high economic value of such merchantable timber boles. By not including product carbon, studies may overestimate the unit costs by percentages in these ranges noted above.

In considering the carbon consequences, every paper in this volume addresses the above- and below-ground biomass carbon and most explicitly account for soil carbon. However, the carbon stored in detritus and in forest products is not explicitly considered in most of the papers.

## 5. UNIT COSTS AND BENEFITS

In evaluating the costs and benefits of a project, it is important to draw a system boundary within which these would be evaluated. By selecting to report costs only up to the roadside (not to the mill-site or market place), the study papers include the cost of harvesting wood but exclude the costs and carbon emissions associated with transporting the produce to the market. This also avoids the need to collect data and make projections of the location of mills which will likely change if a large magnitude of projects have to be implemented in order to significantly reduce nationwide emissions.

### 5.1. Costs

The costs of carbon storage of a mitigation option include: (i) the present value of project costs sufficient to cover the project's development and the expenses and incentives for its ongoing operation; and (ii) the present value of the project's opportunity cost. Swisher<sup>35</sup> refers to the present value of future project costs as an endowment.

The present value of project costs should include the initial cost of establishing the project, cost of silvicultural operations, management, extension services, protection, and cost of monitoring the project's performance. For perpetual management of options, the benefits derived at the end of each rotation may be sufficient to cover the future management and maintenance costs of at least the next rotation.

The 1990 IPCC report on Response Strategies to Climate Change reviewed the literature available on forest mitigation option costs and

benefits until that period.<sup>36</sup> The unit cost estimates have been improved in several ways since the IPCC report. One, unit costs have been estimated for individual countries by different types of mitigation options and forest types, rather than by regions or for the globe as a whole. For example, Dixon *et al.* estimate costs for 94 countries, and averages by latitude, on the basis of surveys and information gathered from the published literature.<sup>7</sup>

Other cost components like land rental (opportunity costs), maintenance, and monitoring and evaluation, which were not included in the earlier IPCC report, are now being addressed.<sup>12</sup> The opportunity cost evaluation is important since it captures the benefits derived from land use in the absence of a mitigation option. Opportunity cost may be evaluated using various methods, depending on the land in question and the likelihood of producing various goods and/or services if it is not used for the given option. These approaches include land rent, land market price and net benefits obtainable from an alternative land use. In all these cases, land values and benefits from alternative use should be adjusted to account for existing significant price distortions due to subsidies, zoning regulations, etc. Deriving opportunity costs for many developing countries or countries with economies in transition is particularly difficult. Opportunity costs within a country may vary significantly with proximity to areas with rapid economic growth.<sup>37</sup> Earlier studies estimated land rental costs at \$148 on average per hectare for the US,<sup>25</sup> and land purchase price between \$400 and \$1000 per hectare by Sedjo and Solomon.

Land prices are likely to be lower in the developing countries. For Thailand, Wangwacharakul and Bowonwiwat report the present value of the opportunity cost of land to be between \$44 and \$89 per hectare.<sup>37</sup> For degraded lands that are suitable for reforestation, e.g. in India, the land price is very low (\$20/ha).<sup>38</sup> For China, the forest lands are already allocated for forest development, while the dry croplands are only for agroforestry development. Thus the opportunity cost of non-forestry land use or land classified for forestry may be close to zero.<sup>39</sup>

The papers in this volume include estimates of the costs of forest protection, which has not been addressed adequately in the past. For sink expansion options, they take into account the initial capital investment and the operating and

maintenance costs, and they also account for the opportunity cost of land. However, they do not explicitly consider the monitoring and evaluation costs.

### 5.2. *Benefits*

In addition to carbon storage, the implementation of a mitigation option will result in other monetary and non-monetary benefits. These benefits may be classified into direct and indirect benefits depending on their role in, and level of, economic activity, and forest values. Direct benefits may include goods such as fuelwood and timber and services such as recreation. Indirect benefits may include such items as employment for local inhabitants, air pollution and microclimate control, watershed protection, and the development of social benefits, schools, roads, hospitals, etc. Forest value is derived from the stock in the forest as a resource which has a recognized value in addition to the above benefits. This value may be influenced by concern for future generations, social status, etc.

There is no consensus at present on the monetary value of reducing a unit of atmospheric carbon. Preliminary US fossil-fuel carbon tax estimates to stabilize climate change range between \$20 and \$200 per tonne of carbon.<sup>40,41</sup> Most of the F-7 unit cost estimates for forestry mitigation options fall well below this range, and for India they are also below the unit costs of India's energy efficiency options.<sup>38</sup>

A unique feature of the papers in this volume is the explicit evaluation of the direct benefits which may be derived from the sale of timber and other forest products. The benefits are sufficiently large to offset the life-cycle cost of many sink expansion options. In effect, carbon may be sequestered at a net benefit to society. The India paper also notes that from a farmer's perspective, carbon sequestration projects may still not be cost effective because of his high cost of borrowing money.

Winjum and Lewis<sup>13</sup> have demonstrated the significance of including the forest stock opportunity cost, using the value of growing stock (that could be derived if the stock were to be liquidated) based on data from 30 plantations in Sedjo.<sup>42</sup> They show that without growing stock costs, the median value of storing carbon is  $-\$48/\text{t C}$  for temperate and  $-\$32/\text{t C}$  for tropical plantations. With the growing stock costs included, the costs increase, but they are much closer at  $-\$22$  and  $-\$24$  per t C,

respectively, largely due to the relatively higher interest rates in developing countries.

Although the papers in this volume do not address the forest stock value issue explicitly, a forthcoming paper by Kadekodi and Ravindranath for India<sup>15</sup> in the F-7 series of papers illustrates that the total value (direct and indirect) of the forest is almost 2.5 times the market value of forest products generated by mitigation options. Accounting for the total value of the forest could significantly increase total benefits, which may more than offset the total costs of a mitigation option.

### 5.3. *Comparing costs and benefits with carbon storage*

Ideally, in determining the net benefit of a mitigation option, one would include the monetary benefit of storing carbon. However, as discussed above, it is not possible to assess the current and future economic damage that carbon might cause. Estimates of such damage for the United States have been controversial and cover a broad range.<sup>40,41</sup> Hence, the papers in this volume used several indicators of cost-effectiveness to report the unit costs and benefits of storing carbon.

For each of the categories of options outlined in Section 2, a consistent evaluation of monetary and carbon implications is necessary. The consistency would allow comparison of options across categories and with options in other sectors such as energy and agriculture. Also, this will allow for an aggregation of the monetary and carbon implications across options. Different indicators of cost effectiveness of an option to store or avoid carbon emissions are discussed in the following sections.

5.3.1. *Initial cost per hectare and per tonne of carbon.* This includes initial costs only, and does not include future discounted investments needed during the rotation period. The indicator would provide useful information on the amount of resources required at the beginning to establish the project.

Most cost studies<sup>6,7,43</sup> estimate this indicator. The other cost components and the option's benefits are often ignored. The studies take into consideration the carbon stored in live biomass and most account for soil carbon. The Dixon study uses the mean stock of carbon to indicate the amount of carbon that would be stored by a mitigation option. The other studies report several estimates of the cost per tonne of



carbon, but their method of carbon estimation is unclear.

5.3.2. *Present value of cost per hectare and per tonne carbon.* This is the sum of initial cost and the discounted value of all future investment and recurring costs during the lifetime of the project. For rotation projects, the costs of second and subsequent rotations would be paid for by the revenues derived from the preceding rotations and thus would not be included in estimating the present value. Swisher uses this indicator to evaluate project cost-effectiveness.<sup>13</sup>

5.3.3. *Net present value (NPV) per hectare and per tonne carbon.* This indicator would provide the net direct benefit to be obtained from the project. For most plantation and managed forests this should be positive at a reasonable discount rate. For options such as forest protection, the NPV indicator is also positive if indirect benefits and forest value are included, both of which are subject to controversial evaluation. Appendix B explains the mathematical formulation for deriving this indicator for plantations and managed forests.

5.3.4. *Benefit of reducing atmospheric carbon (BRAC).* This proposed indicator would provide the benefit of reducing atmospheric carbon.<sup>26</sup> It expresses the NPV of a project in terms of the amount of atmospheric carbon, as opposed to net emissions, that is reduced. In so doing, it captures the atmospheric residence time of carbon. The formulation of the indicator varies with the rate at which economic damage might increase. Appendix C provides a formulation for deriving BRAC when the economic damage caused by atmospheric carbon increases at the real societal rate of discount.

A useful way to present the establishment cost per tonne of carbon or per hectare is to plot a cost of conserved carbon (CCC) curve.<sup>25</sup> The curve shows the amount of carbon that could be stored at increasingly higher establishment costs as illustrated in the papers in this volume. Other indicators could also be used to plot similar curves.

## 6. CARBON AND COST SCENARIOS

The land-use and wood-product demand scenarios when combined with the unit carbon sequestration and unit cost estimates developed in and yield future scenarios of carbon and cost of mitigation options. The total cost may be compared with the current government budget

for afforestation or forest management programs, and with the overall government budget as reference. The F-7 studies show that the budget allocated to the forestry sector is small, and that a much larger expenditure is warranted given the considerable reduction in emissions and carbon sequestration potential of the forest sector to mitigate climate change.

## 7. BARRIERS AND INCENTIVES FOR CARBON SEQUESTRATION

The scenarios provide useful information to policy makers regarding the total and average cost to sequester carbon. However, this information is not adequate to develop policies and measures to implement carbon sequestration projects. A diverse array of criteria will have to be satisfied before a project can be implemented. These may include the ease of implementation, an identification of the project's beneficiaries and losers, institutional and legal considerations, etc. Each study paper in this volume identified and discussed problems specific to the implementation of carbon storage projects.

## 8. CONCLUSIONS

This paper describes the Comprehensive Mitigation Assessment Process (COMAP), a bottom-up methodological framework, that was used in the assessment of carbon sequestration potential by researchers from the participating F-7 network countries. The discussion highlights several themes that have not been commonly addressed in evaluating the costs of forestry mitigation options. These include end-use scenarios, which have not been used in assessing land and wood products demand for carbon sequestration purposes. The uncertainty regarding the future value of carbon, which requires that sustainable carbon sequestration be pursued, is discussed. The explicit inclusion of the carbon storage potential on land and in products is noted. Cost-effectiveness indicators are reviewed which account for the reduction of atmospheric carbon rather than emissions, and an explicit accounting of monetary non-carbon benefits, like those derived from forest products, which may completely offset a project's cost and the opportunity costs of pursuing forestry options.

Using this methodology, the studies in this volume show that many currently deforesting

countries offer the potential to cost-effectively reduce emissions from forestry sources. Some countries have already halted deforestation and may begin to sequester significant amounts of carbon in the near future. Thus forests may begin to act as stop-gap sinks of atmospheric carbon while measures to restrain emissions from fossil fuels are being sought.

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#### APPENDIX A ESTIMATING CARBON STORED BY PLANTATIONS AND FORESTS MANAGED IN PERPETUAL ROTATION

Total carbon stored

$$= \text{Land carbon} + \text{Product carbon}$$

Land carbon = (Vegetation + soil

$$+ \text{decomposed matter}) \text{ carbon}$$

$c_t$  = total carbon ha;  $c_v$  = vegetation carbon;  $c_d$  = decomposing matter carbon;  $c_s$  = soil carbon;  $T$  = rotation period.

Summarizing the formulas shown below for each type of carbon storage:

$$\text{Carbon stored per ha} = (c_v \times T/2) + (c_d \times T/2)$$

$$+ (c_s \times T) + \sum_{i=1}^n c_{pi} \times n_i$$

I. Vegetation carbon: for the plantation response option, consider that the plantation is operated in rotation for an indefinite time period. This would ensure that at least 1/2 of the carbon sequestered by an individual plot is stored away indefinitely. The formula for estimating the amount of carbon stored per hectare is:

$$\text{Vegetation carbon stored per ha} = c_v \times T/2,$$

where  $c_v$  = average annual net carbon sequestered per hectare, and  $T$  = rotation period.

II. Decomposition is equivalent to storing carbon: the decomposing biomass on land also creates a stock of

carbon. In perpetual rotation analysis, this carbon stored in the biomass may be estimated using the following formula:

Decomposed matter carbon stored per ha

$$= c_d \times T/2,$$

where  $c_d$  = average annual carbon left to decompose per hectare, and  $T$  = decomposition period.

III. Soil carbon: there is considerable uncertainty in the literature regarding the soil carbon content and the influence of factors that affect it. Hence, we should analyze economic costs and benefits with and without considering soil carbon. Where soil carbon data are not available, soil carbon data from other countries with similar conditions may be used. Note that the increase in soil carbon is more significant (i.e. a higher percentage of total carbon benefit) where the current above-ground biomass is low, and vice versa. Further, we assume that the soil carbon loss and gain during harvesting and regrowth is very small compared to initial gain on degraded land.

$$\text{Soil carbon stored per ha} = c_s \times T,$$

where  $c_s$  = increase in soil carbon per hectare, and  $T$  = rotation period.

IV. Fate of forest products: if the forest products are renewed continually, they can store a stock of carbon over an infinite period. The amount of carbon stored in the form of products will depend on the product life. The longer the product life the more carbon will be stored away. The amount stored over an infinite horizon will increase with product life according to the formula:

$$\text{Carbon stored per ha} = \sum_{i=1}^n c_{pi} \times n_i$$

where  $c_{pi}$  = amount of carbon stored per hectare in product  $i$ , and  $n_i$  = life of product  $i$ .

We assume that the product decomposes instantaneously at the end of its life and not continually over its life.

#### APPENDIX B ESTIMATING NET PRESENT VALUE OF PLANTATIONS AND FORESTS MANAGED IN PERPETUAL ROTATION

This note explains the computation of the net present value (NPV) for a plantation or forest which is managed in perpetual rotation. We provide the formulas for computing the NPV for one rotation on a single plot, that for perpetual rotations on a single plot and finally for a mosaic of perpetual rotations on multiple plots. The NPVMP shown in the last equation should be used to calculate the NPV indicators shown in Item 4.

I. NPV per hectare for one rotation on one plot:

$$\text{NPV} = \sum_{t=0}^T (R_t - C_t) e^{-rt},$$

where  $R$  = revenue per hectare in time  $t$ ,  $C_t$  = cost per hectare in time  $t$ ,  $r$  = rate of discount,  $T$  = rotation age in years, and  $e$  = natural log base.

II. NPV per hectare for perpetual rotations on one plot (NPVP):

$$\text{NPVP} = \text{NPV} (1 - e^{-rT}).$$

Note that for coppice plantations, a rotation should be taken to mean the length of time until replanting. The coppice harvest and costs should be treated as intermediate output and costs.

III. NPV per hectare of perpetual rotations on multiple plots (NPVMP):

The NPV of perpetual rotations on multiple plots is

$$NPV = NPVP \sum_{t=0}^T e^{-rt}.$$

$$NPV = NPVP(1 - e^{-rT})/(1 - e^{-r}).$$

The NPVMP is obtained by dividing the above equation by  $T$ , which gives:

$$NPVMP = NPVP(1 - e^{-rT})/T(1 - e^{-r}).$$

### APPENDIX C ESTIMATING THE BENEFIT OF REDUCING ATMOSPHERIC CARBON (BRAC)

For the case where the economic damage caused by carbon increases at the rate of discount, we can estimate BRAC using the following formulation:

$$BRAC = NPV / \left[ \frac{1}{a} \sum_{t=0}^{T_e} C_t \right],$$

where NPV = net present value of benefits,  $a$  = decay rate of carbon,  $T_e$  = time duration of carbon flows, and  $C_t$  = net carbon flow in time  $t$ .